

**Ando, Lavrov, and Segawa Reply:** In the preceding comment [1], Jánossy, Simon, and Fehér (JSF) offered an alternative picture to explain our recent findings [2] and argued that it is unlikely that the charged stripes exist in hole-doped antiferromagnetic  $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$  (YBCO). They proposed that the anomalous behavior of the magnetoresistance (MR) is essentially due to an in-plane anisotropy in the resistivity of the *bulk*. Here we show that it is extremely unlikely that the charge transport through the bulk is taking place in the antiferromagnetic YBCO, and thus the formation of charged stripes in this system is an inevitable conclusion.

The staggered magnetization of the antiferromagnetic (AF) YBCO lies in the *ab* plane and there should be two equivalent easy axes for the spins. When a small number of holes are doped into the  $\text{CuO}_2$  planes that have the Néel order, there are four possible phases for the system: (a) the system is a single domain AF (all the spins lie along one of the easy axes) and the doped holes are distributed over the system, (b) an AF domain structure is formed (with alternating direction of the easy axis) and the doped holes are distributed in the domains, (c) an AF domain structure is formed and the doped holes are confined in the domain walls (in other words, charged stripes constitute the domain walls), and (d) a macroscopic phase separation takes place into the AF regions and doped non-magnetic ones.

The ESR experiment by JSF demonstrates [1] that there is a magnetic domain structure, which gives evidence against the case (a). The equivalence of the *a* and *b* axes follows also from the symmetry of the MR [2]. Case (d) can easily be eliminated, because in this case the system must contain an admixture of superconducting phase (remember that YBCO is either an antiferromagnet or a superconductor); experimentally we have never observed such a macroscopic phase separation. We can also eliminate case (b), because the domain walls in this case have a very large energy cost (of the order of  $NJ$ , where  $N$  is the number of nearest-neighbor spin bonds along the domain walls and  $J$  is the antiferromagnetic interaction energy). Such a large energy cost of the domain walls would cause a transition into a phase without domain walls [case (a)] at low temperature. Therefore, the case (c) is the only possible phase in antiferromagnetic YBCO given the AF domain structure is observed down to low  $T$  [1]. In case (c), the energy cost of the domain walls is grossly smaller than that in case (b) due to the spinless stripes. The above discussion makes it clear that the charge transport through the bulk is unlikely to be taking place in the antiferromagnetic YBCO.

JSF argued that an array of charged stripes cannot respond to the magnetic field because the Coulomb repulsion would make it extremely rigid. This is their central reasoning to reject the stripe scenario. However, the Coulomb repulsion does not necessarily make the stripes rigid; actually, the stripes in cuprates are expected to be

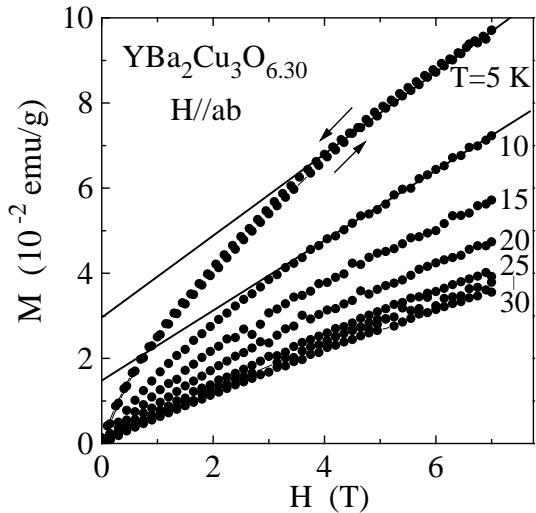


FIG. 1. Magnetization of  $\text{YBa}_2\text{Cu}_3\text{O}_{6.3}$  for  $H \parallel ab$ .

fluctuating, meandering, and liquid-like [3].

The question of how the striped structure respond to the external magnetic field and what is the mechanism for coupling is yet to be clarified. In our Letter [2], we suggested some local ferromagnetic moment to be associated with the stripe structure. To confirm this possibility, we have recently performed measurements of the bulk magnetization of a  $\text{YBa}_2\text{Cu}_3\text{O}_{6.3}$  crystal. It turned out that the ferromagnetic contribution to the magnetization actually exists, since the fits to the linear high-field  $M(H)$  data show noticeable positive intercepts, Fig. 1. The characteristic field for the ferromagnetic moment to be established,  $\sim 4$  T, is well correlated with the threshold field in our MR data [2]. Even a weak hysteresis is observed in the magnetization curves at 5 K.

To conclude, both the charged stripes and weak ferromagnetism doubted in the Comment [1] should inevitably be taken into account to understand the nature of antiferromagnetic  $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ . More direct investigations would enable us to elaborate on the details of the striped-phase structure and to understand how exactly the stripes are affected by the magnetic field.

Yoichi Ando, A. N. Lavrov, and Kouji Segawa  
Central Research Institute of Electric Power Industry,  
2-11-1 Iwato-kita, Komae, Tokyo 201-8511, Japan

74.25.Fy, 74.20.Mn, 74.72.Bk

---

- [1] A. Jánossy, F. Simon, and T. Feher, Preceding Comment.
- [2] Y. Ando, A. N. Lavrov, and K. Segawa, Phys. Rev. Lett. **83**, 2813 (1999).
- [3] S. A. Kivelson, E. Fradkin, and V. J. Emery, Nature **393**, 550 (1998); J. Zaanen, M. L. Horbach, and W. van Saarloos, Phys. Rev. B **53**, 8671 (1996).